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OBSERVATIONAL AND FIELD ASPECTS OF GROUND-WATER FLOW AT HANFORD

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INTRODUCTION

At Hanford, the semi-arid climate, the permeable surficial sediments, and the deep water table combine to produce a situation wherein most of the radioactivity of the chemical effluents is trapped by ion exchange and adsorption phenomena in the sediments as the waste percolates down to the water table. Those wastes that reach the water table move with the ground water toward the Columbia River. This paper will follow this movement, indicating what is known about it and what needs to be found out.

GENERAL STATEMENT

Geological and hydrological studies at Hanford have indicated what aquifers are present and their continuity. Hydraulic field tests have been conducted to determine the field permeability of the sediments, expressed, commonly, as the quantity of water in gallons transmitted daily through each square foot of cross section of the material under a hypothetical slope of water level of 1 ft per ft. Permeability, together with measurements of water levels in wells to give the actual slope of the water table, gives the average quantity of water moving per square foot of cross section of the aquifer and the approximate direction in which it is moving. Knowing the effective porosity of the material and the quantity of water flowing, the average velocity can be calculated. It is therefore possible to estimate the average rate at which radioactive waste would travel if it moved uninhibited with the ground water, about where it would be discharged, and the approximate path it would take to get there.

MEASUREMENT AND ESTIMATION OF AQUIFER PERMEABILITY

At Hanford some 200 feet of sand and gravel of glacial origin (Glaciofluviatile sediments) immediately underlie the waste disposal sites. Below this is an earlier glacial formation (Ringold formation) as much as 800 feet thick, consisting of silts, sand, and gravels with several clay beds. The water table, which is from 200 to 350 feet below disposal sites, lies largely within the Ringold formation but extends in some places into the overlying glaciofluviatile sediments. Below these two major units is the relatively impermeable basalt.

The hydraulic characteristics of Hanford aquifers have been measured and estimated by a variety of established field methods. These include evaluation of data from pumping tests, specific capacity tests, tracer tests, cyclic fluctuations of water level, and hydraulic gradients. Mutually consistent results show that the permeability of the glaciofluviatile sediments ranges from about 10,000 gpd/ft^2 to more than 60,000 gpd/ft, and the permeability of the underlying Ringold deposits ranges from about 100 to 600 gpd/ft^2 (1, 2). A summary of results is given in the following table:

AQUIFER TESTED	AVERAGE FIELD PERMEABILITY (gpd/ft^2) CALCULATED FROM: Pumping tests	Specific Capacity tests	Tracer tests	Cyclic fluctuations	Gradient method
Glaciofluviatile	1[illegible],000-67,000	10,000-65,000	> 6[illegible],000	17,000-57,000	---
Glacial and Ringold	900-5,000	1,000- 4,000	----	1,000- 6,000	---
Ringold	50- 600	60- [illegible]00	----	150- 500	100 - [illegible]

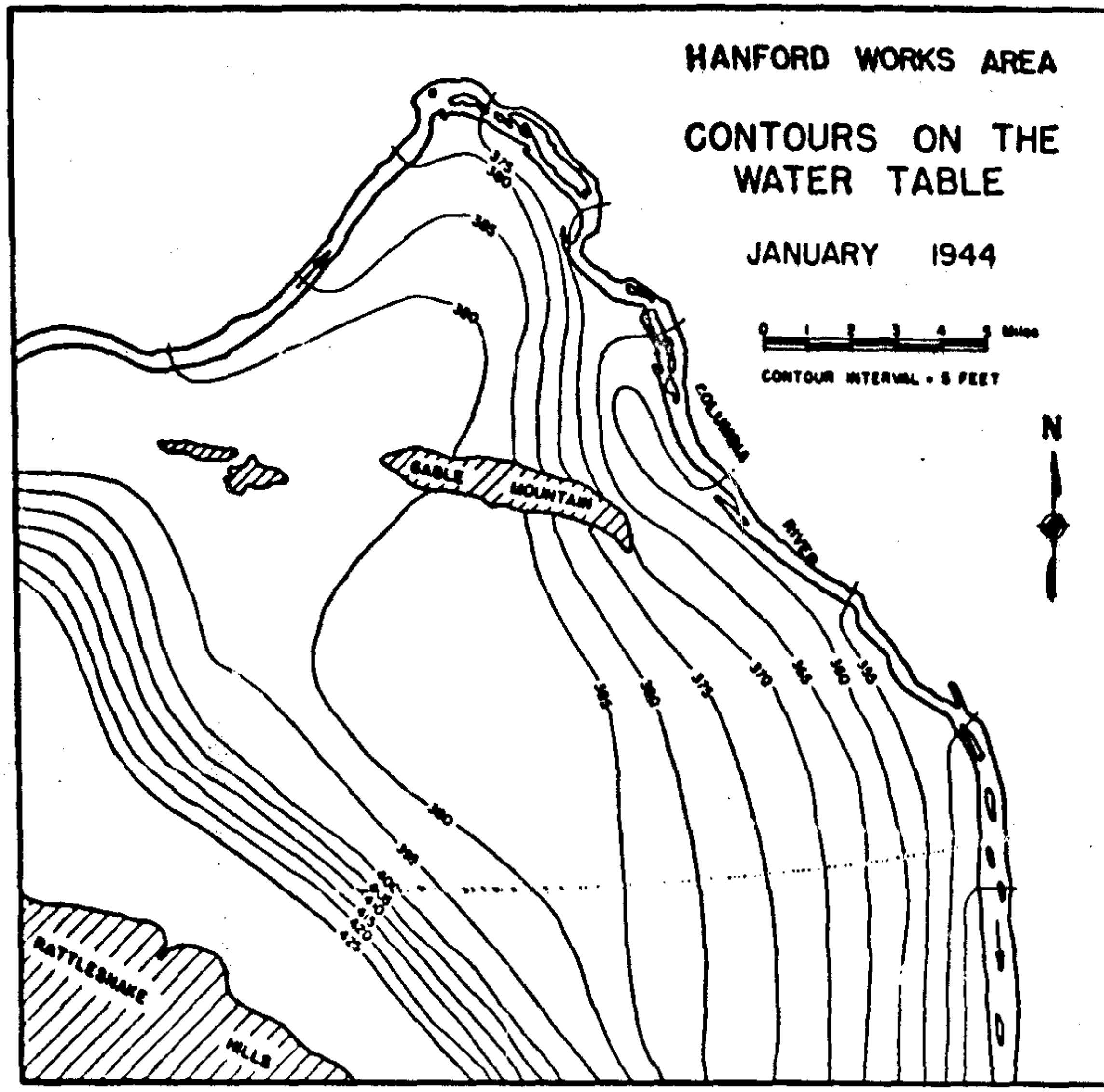
WATER-LEVEL CONTOURS

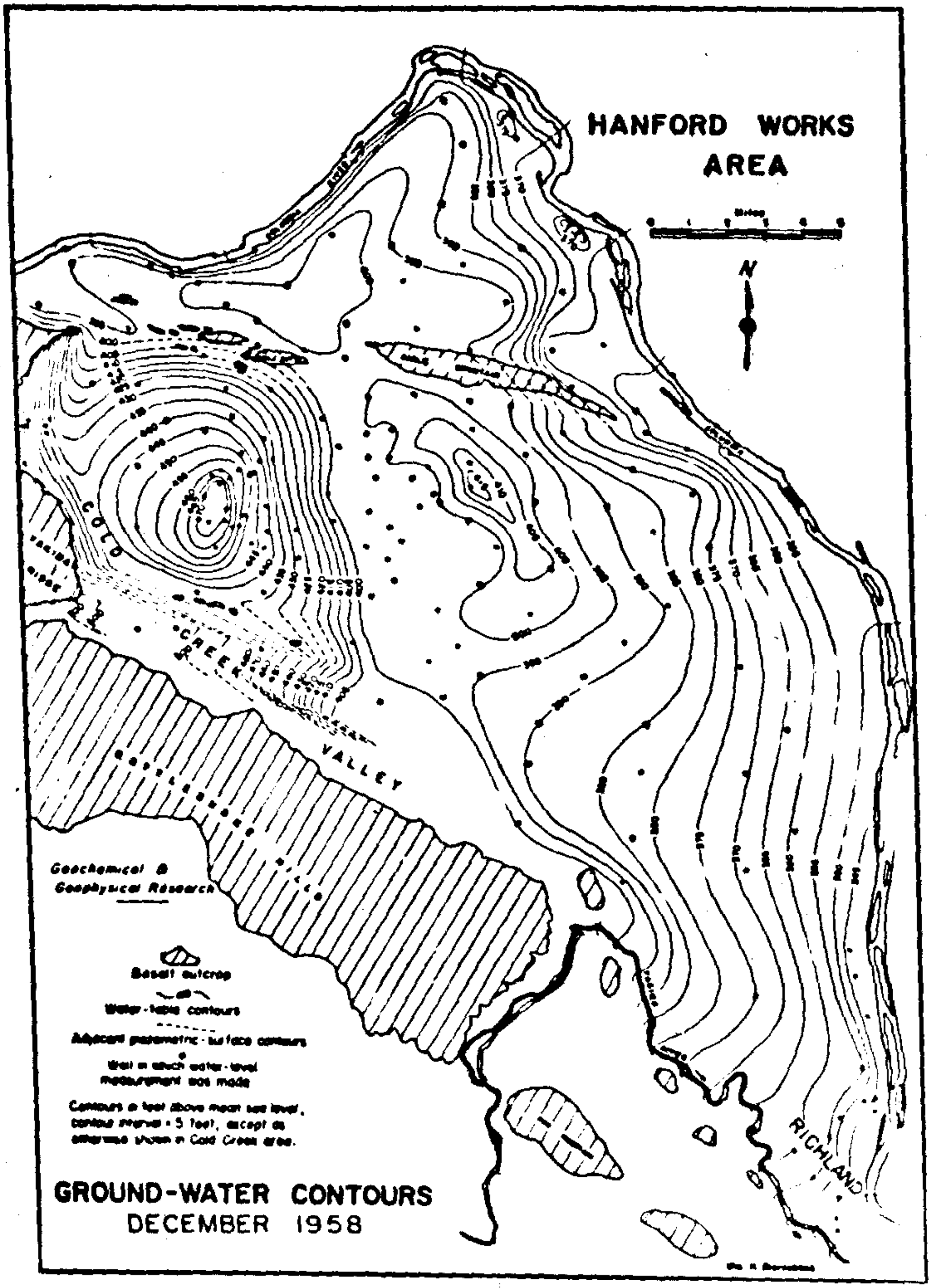
Since 1944 the chemical processing plants have discharged to ground over 35 billion gallons of liquid effluents. Such large volumes have had a profound effect upon the regional water table. Figure 1 shows the contours on the water table interpreted from the earliest measurements of water level in wells and from general hydrological knowledge. Similar maps have been prepared periodically over the years and with increasing accuracy as more wells became available. The ground-water contours as of December 1958 are shown in Figure 2. Two distinct ground-water mounds have been created on the water table, their location, elevation, and shape depending upon the location of the disposal sites which fed them and upon the nature and geological attitude of the sedimentary formations in which they occur (3). It is of importance to study these mounds since they determine the direction and rate of flow of the ground water and this in turn is important in the proper location of disposal sites and in following the underground movement of mobile materials.

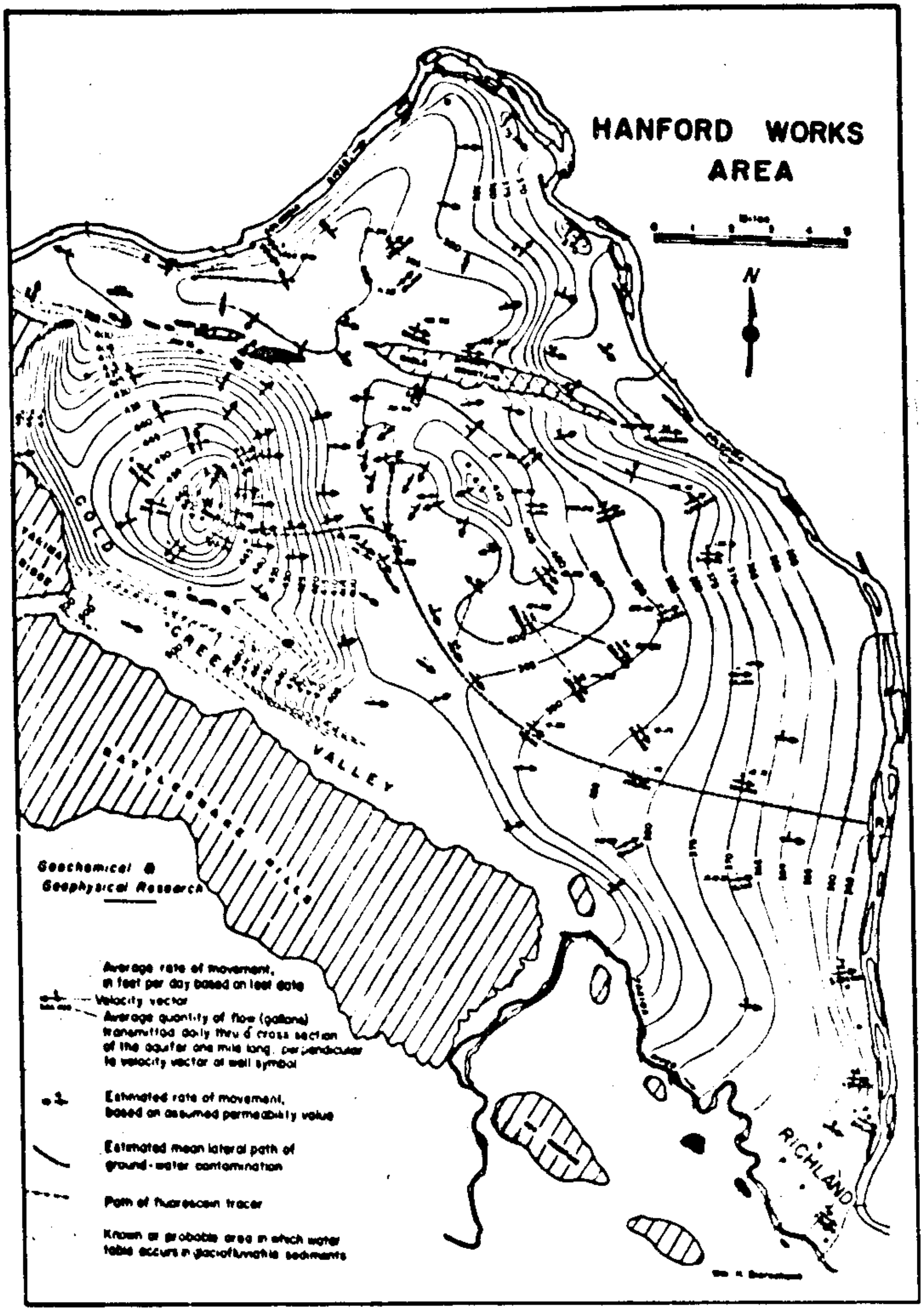
MOVEMENT OF GROUND WATER AND CONTAMINATION

Direction of Movement

In the absence of more precise data, it is assumed that ground water always moves in the direction of the hydraulic gradient. Therefore, the best means of determining the direction of movement is by drawing lines perpendicular to ground-water contours, from high to low head. (See velocity vectors, Figure 3). Strictly, even a perfect contour map of the water table would show only the horizontal direction of movement of the ground water at the water table. The hydraulic gradients are three-dimensional, however, and the water moves not only along the water table but also to depths below the water table and generally upward again to the water table at some other place.


HANFORD WORKS AREA
CONTOURS ON THE WATER TABLE
JANUARY 1944
CONTOUR INTERVAL = 5 FEET
N
COLUMBIA
RIVER
SABLE
MOUNTAIN
RATTLESNAKE
HILLS
385
380
375
370
365
360
355
405
410
415
420
425


HANFORD WORKS AREA
N
COLD CREEK VALLEY
RICHLAND
Geochemical & Geophysical Research
Basalt outcrop
Water-table contours
GROUND-WATER CONTOURS
DECEMBER 1958


HANFORD WORKS AREA
N
COLD CREEK VALLEY
RICHLAND
Geochemical & Geophysical Research
Average rate of movement, in feet per day based on test data
Velocity vector
Average quantity of flow (gallons) transmitted daily thru a cross section of the aquifer one mile long, perpendicular to velocity vector at well symbol
Estimated rate of movement, based on assumed permeability value
Estimated mean lateral path of ground-water contamination
Path of fluorescein tracer
Known or probable area in which water table occurs in glaciofluviatile sediments

As Figure 3 indicates, the present pattern of ground-water movement underlying Hanford Works has changed fundamentally during the 14 years of plant operation, owing to concurrent changes in water-table form. In brief, the zone saturated by infiltered waste effluents creates a ground-water divide, roughly concave to the south and enclosing disposal sites on the west, north, and east. From the northern or outer flank of this divide, the artificially recharged water largely moves radially northwestward and northeastward. From the southern or inner flank of the divide, the infiltered wastes converge and move generally southeastward and then more eastward in a relatively narrow band.

The directions of movement described above are those which would be taken currently by any radioactive waste products infiltering to the water table from an overlying disposal site. It must be recognized, however, that deposits of sand and gravel such as comprise the glaciofluviatile and Ringold sediments are, in varying degree, lenticular; thus in the coarse materials wastes would move more rapidly than in the fine materials. In addition, if the lenses are elongated in one direction, or the strata are inclined steeply, the direction of flow will incline in the direction in which water moves more easily than in another. Furthermore, a waste contained in a stream of ground water disperses both along and transverse to the direction of flow. As pointed out by Theis (4), dispersal in the direction of flow reduces the concentration of the contaminant if the waste is a slug temporarily introduced, and gives a warning at a locality downstream of the approach of a continuously introduced waste stream. Dispersal across the direction of flow spreads a contaminant more widely but reduces the concentration.

Such factors as heterogeneity, anisotropy, and dispersal assume great importance in determining the path of contaminants in the ground water. Consequently, the estimated mean lateral path of ground-water contamination shown in Figure 3 is taken to represent the probable minimum distance of travel from beneath disposal sites W and E to the Columbia River, R. Based on the hydrologic conditions inferred in Figure 3, a minimum path from W to R of about 110,000 ft (about 21 miles) and from E to R of about 95,000 ft (about 18 miles) appears reasonable.

Rates of Movement

The rate of ground-water flow is fixed by the vector quantity describing the maximum hydraulic gradient. Darcy's law for laminar flow is applicable but only enables the estimation of average velocities. Variation from the average is likely to be considerable, so that some small fraction of the flow may move at several times the average velocity. For example, fluorescein tracers have been detected in observation wells at various distances down-gradient from injection wells. Rates of travel of the dye, based on the first detected arrival, have been measured to be 170 ft/day through 50 ft of travel in one case, 170 ft/day through 11,500 ft and 195 ft/day through 13,200 ft in a second case, and 440 ft/day through 8,800 ft in a third case. These velocities are 3 to 4 times greater than the average calculated values.

On the basis of measurements and estimates of aquifer characteristics, average ground-water velocities have been calculated according to the equation -

$$v = \frac{P\ I}{7.48\ p}$$

where v is the velocity in feet per day,
P is the average field permeability in gallons per day per square foot,
I is the hydraulic gradient in feet per foot, and
p is the effective porosity or specific yield in percent

The flow rates are shown in Figure 3. The map shows velocity vectors, with numerical values of average rate of movement in ft/day, as well as the quantity of water in gallons flowing in 1 day through a 1-mile-long section of the aquifer perpendicular to and bisected by the velocity vector for those sites where the field permeability has been determined by pumping tests. The volume of flow to the southeast in the glaciofluviatile sediments is in the order of several hundred times that flowing eastward in the Ringold sediments.

Eastward movement from disposal site W (Figure 3) occurs under an average hydraulic gradient of about 20 ft/mile in the Ringold aquifer of permeability assumed to be 300 gpd/ft^2. Average rates of movement are therefore only about 1-1/2 to 2 ft/day. Subsequent southeastward movement in the highly permeable glaciofluviatile sediments occurs chiefly under shallow gradients of only a few tenths of a foot per mile. Average velocities of about 7 ft/day were computed for most of this stretch. Direct eastward movement to the Columbia River through glaciofluviatile sediments is inhibited by the southern end of the eastern ground-water mound. Instead, general movement occurs more to the south through Ringold deposits under the influence of a moderate gradient of roughly 5 ft/mile, at an average velocity of 1 ft/day or less.

Travel time. -- Based on the average ground-water velocities shown in Figure 3, a "travel time" of about 180 years is calculated for ground-water flow from W to R, and about 175 years from E to R. It must be emphasized, however, that the maximum rate of movement of the ground water and even of some materials dissolved in it (e.g. ruthenium-106 and nitrates) may be many times the average, while those dissolved constituents that enter into sorption reactions [illegible] strontium-90 and cesium-137) may move far slower than the water [illegible] "isotope travel time" is suggested as a more descriptive term for the actual occurrence of concern inasmuch as several factors other than ground-water movement affect the available decay interval. Studies at the University of California Sanitary Engineering Research Laboratory have shown that (a) hydraulic phenomena produce velocity variations that bring about a longitudinal mixing of selected intruding and displaced fluids. A diffuse zone or "concentration front" forms rather than a sharply defined interface. The depth of this zone increases in proportion to the distance traveled due to portions of the intruding contaminant moving at velocities exceeding the average; and (b) ion exchange reactions may modify the propagation of a radiocontaminant in two ways: 1) the median velocity of the contaminant front will be predictably less than that of the liquid front, and 2) the depth or diffuseness of the front may be modified over that resulting from purely hydraulic phenomena. When the radiocontaminant is not selectively sorbed by the exchange medium, its front will become increasingly diffuse as it progresses through the medium. When the radiocontaminant has a selective affinity for the medium, as may be the case with strontium or cesium as the displacing cation, the front may not become more diffuse with distance but rather may tend to sharpen as propagation continues (5,6).

Empirical data obtained from radiologic monitoring of wells at Hanford have shown that the chemical form of Ru^{106} in Hanford wastes is little affected by ion exchange, and anionic components of waste, such as nitrates, are apparently not affected at all. In one case radioruthenium moved southeastward about 8 miles from an eastern disposal site (near E, Figure 3) in less than 1 year at rates approaching 160 feet per day. Nitrate concentration increased to about 500 ppm in well 699-20-20 (Figure 3) before trace concentrations in the order of 10^{-7} $\mu c/cc$ of Ru^{106} appeared. This followed an approximately 18-month period of negligible supply of cooling water to the eastern swamp, during which the eastern mound subsided to the extent that a favorable hydraulic gradient existed from site E to well 699-20-20. As mentioned previously, subsequent tracer tests in this area showed that first arrivals of fluorescein in wells downgradient from the injection well had traveled at average linear rates of 170 and 195 ft/day over distances of approximately 2.2 and 2.5 miles, respectively. Obviously, precise determinations cannot now be made at Hanford of the various "isotope travel times" based on the present qualitative knowledge of the various complicating factors.

FUTURE STUDIES AND CONCLUSIONS

Additional geological and hydrological information is needed in waste disposal studies. The techniques of ground-water studies used for estimating ground-water characteristics give average values--average velocity and average path of flow. In radioactive waste disposal the average is necessary as a starting point or a point of reference, but it is not good enough. For instance, the factors of heterogeneity and anisotropy of aquifers assume great importance in waste disposal. The important effects of such irregularities in the various geologic units upon the rate and direction of waste movement require that the geology be learned in great detail and that many wells be drilled to get these details. During 12 years of continuous well drilling at Hanford since the [illegible] waste disposal research program began in 1947, 547 wells have been drilled for various purposes, totalling more than 107,000 feet. During the next 10 [illegible] it is contemplated that an average of about 11 wells per year [illegible] 5,000 feet per year will be required for research purp[illegible] T[illegible] needed to (a) monitor any movement of ground-[illegible]

(b) provide structures for hydraulic investigations permitting further evaluation of aquifer characteristics, (c) provide sediment samples for laboratory evaluation of ion exchange capacity, permeability, and mineral content, and to furnish soil column material for crib-life evaluations, and (d) provide basic geologic (stratigraphic) data. Items b, c, and d will provide data that permit predictions to be made of the probable behavior of wastes in the ground, and of the paths and rates of travel toward points of possible exposure. Item (a) will provide information on the actual behavior, information that can then be correlated to the data from which the predictions are made.

Because knowledge of the processes of dispersion is incomplete, this phenomenon must be further investigated in the field since the effective dispersion in the field is probably larger than indicated by laboratory experiments. A special 23-well field-scale facility for the study of dispersal phenomena during movement of ground water is under construction at the 699-62-43 site. A calcium nitrate solution spiked with Sr^{85} (65-day half life) will be charged to an injection well under constant head to permit determination of strontium and nitrate breakthrough curves. These results will be correlated to those obtained from a laboratory soil column experiment using aquifer sediments from this site with the same tracer solution. The sinking of high-density wastes in the aquifer will also be observed by sampling the ground water at various depths in the 30-foot aquifer.

A geophysical seismic program is also being considered. It is hoped that such a technique would tend to improve forecasting of drilling needs, positioning of wells, completing of drilling projects at faster rates, and eventually reducing overall drilling needs.

In conclusion, a hydrogeological survey of waste-disposing sites must be extremely thorough. The current state of knowledge concerning aquifer characteristics and ground-water movement at Hanford has been presented herein. Estimates

HW 54 4

have been made of the average rate at which the ground water would travel, about where any ground-water contamination would discharge into the Columbia River, and the approximate path it would take to get there. However, a considerable expansion of basic knowledge of ground-water movement and the geochemistry involved is required in order to insure that the geology and hydrology have been properly interpreted.

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